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THERMAL MANAGEMENT INVESTIGATIONS IN CERAMIC THIN DISK LASERS

William P. Latham et al.

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Technical Note

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AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

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//Signed//
WILLIAM P. LATHAM, DR-III
Project Officer

//Signed//
JORGE E. BERAUN, DR-IV, DAF
Chief, Laser Division

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Thermal Management Investigations in Ceramic Thin Disk Lasers

N. Vretenar[a], T. Carson[b], A. Lobad[c], P. Peterson[c], T. C. Newell*[b], and W. P. Latham[b]
[a]Center for High Technology Materials, Univ. of New Mexico, 1313 Goddard SE, Albuquerque, NM USA 87106
[b]Air Force Research Laboratories, Directed Energy Directorate, 3550 Aberdeen Ave SE, Kirtland AFB, NM USA 87117
[c]Boeing LTS Inc. P.O. Box 5670 MC RN-M1, Kirtland AFB, NM USA 87117

ABSTRACT

Directed Energy applications for thin disk lasers demand improvements in materials, efficiency, thermal management, and most importantly beam quality. At the Air Force Research Laboratory ceramic Yb:YAG materials are being investigated along with various cooling techniques. 10-14mm diameter 0.2mm thick disks are mounted on silicon carbide (SiC), sapphire, and diamond submounts. From a larger platform, more than 6kW power is obtained from unmounted and sub-mounted 35mm diameter disks. In conjunction with thermal modeling, we project a path towards high performance high power lasers.

Keywords: Laser materials; Lasers, ytterbium; Lasers, solid-state; Lasers, diode-pumped; Optical materials

1. INTRODUCTION

Since its inception, thin disk laser performance has evolved to impressive power generation in the multi-kilowatt levels for single disk resonators and nearly 30 kW for multiple disk resonators. Single crystal Yb:YAG thin disk lasers (TDL) now operate at kW powers with greater than 60% slope efficiencies and "wall-plug" efficiencies more than 20% [1-3]. While single crystal materials produce outstanding results, a new alternative is the use of ceramic materials. Highly translucent and low scattering ceramic materials have been produced using purely chemical reactions and nanocrystalline powder sintering in vacuum ovens [8,9]. Large diameter polycrystalline Yb:YAG can be used for area scaling of single thin disk lasers. Spectroscopic and laser characteristics of ceramic Yb:YAG are very similar to those of single crystal. Low power laser results with ceramics have been quite promising with greater than 60% slope efficiency [10]. Taira et al. demonstrated output power intensity of 3.9 kW/cm^2 from a composite all-ceramic $Yb:Y_3Al_5O_{12}$ microchip laser with the maximum thermal stress exceeding twice the tensile strength of single crystal YAG [11].

One of the requirements for directed energy applications is the need for laser beams with a very high, practically Gaussian, beam quality. In this aspect thin disk lasers suffer. Their development and commercial application has been directed towards laser welding where the relatively poor beam quality is not detrimental. There are a number of reasons for this lack of high beam quality. The one that has become the focus of this research is associated with the effects of the high heat load generated in the YAG media. Certainly the chief culprit is associated with the quantum defect between the 940nm pump and 1030nm lasing light. In addition, spurious generation of amplified spontaneous emission takes place. The fraction of this light that is reabsorbed in the media also generates a heat load. Finally, excess absorption of light due to a plethora of causes (color-centers, defects in the YAG, bonding layers, etc...) adds to the problem. Much of this research was established to investigate methods to mitigate these issues.

In this presentation, high power lasing in Yb:YAG ceramic TDL is shown. Our results illustrate that polycrystalline Yb:YAG ceramic thin disk geometry has a strong potential for operation at multi-kW output level. Performance and beam quality are limited in part by the thermal issues inherent to multi-kW pumping and the cooling methods incorporated. These subjects are investigated via experimental measurements and numerical modeling.

*tim.newell@kirtland.af.mil

2. EXPERIMENTAL WORK

Yb:YAG Material and Assemblies

Yb:YAG ceramic thin disks used are manufactured by the Konoshima Corporation. The disks are 200 μm thick and Yb-doped at 9.8%. The diameter is 35-37mm. Disks used in initial high power studies are diffusion bonded to a 1 mm undoped YAG ceramic. The undoped cap serves two purposes. Primarily it aids the suppression of amplified spontaneous emission generated. By being index matched a significant fraction of the spontaneous emission escapes upward through the undoped cap rather than total internally reflected within the Yb:YAG material. The second reason for the undoped cap is to provide rigidity. Without the cap, a 0.2mm thick Yb:YAG disk will immediately disintegrate when subjected to the water jet impingement cooling. The bonding process of Yb:YAG to YAG is performed by Precision Photonics using their chemically activated direct bonding (CADB) technique. The top side of the thin disk assembly is coated with a dichroic anti-reflection (AR) coating. The bottom side of the assembly is coated with a high reflective (HR) coating at both the 940 nm pump and the 1.03 μm laser wavelengths.

The YAG assemblies are either attached to heat sinks or directly to the CuW cooling mount, see Fig. 1(c) & (d). The heat sinks tested are SiC, sapphire, and diamond all with a thickness of 0.5mm. The Yb:YAG/YAG assemblies are attached to the submounts either using an epoxy (for diamond and SiC) or the CADB process (Sapphire). The finished unit is epoxied to a CuW holder around the periphery. With the CuW unit, 26 mm clear aperture is available to pump. The back side of the assembly is then cooled by a water spray. In this work, cooling of the Yb:YAG or heat sink is accomplished by jet-impingement cooling, 2.5 gal/min at 20 °C, directly against the back of the disk assembly.

Since the submounts provide sufficient mechanical rigidity to withstand the water pressures of the cooling spray, the opportunity to examine laser performance without the undoped YAG cap is created. Thus some of the Yb:YAG samples are mounted to the heat sinks without an undoped YAG cap. This provides an opportunity to examine the deleterious role of amplified spontaneous emission.

Experimental Setup

Figure 1 describes the laser cavity and thin disk assembly. In Fig. 1(a) a straight-forward 'I' cavity is built in which the other end of the cavity is a concave output coupling mirror. Fig. 1(b) incorporates an external high power mirror along with the output coupler optic to define a 'V' cavity. This provides a two-pass scenario. In both Fig. 1(a) and 1(b) The main thin disk chamber, dotted line box, contains the Yb:YAG media, multi-pass reflecting mirrors for the pump, and cooling. In the figure, M refers to highly reflective mirrors, OC is the output coupler mirror, 2m radius of curvature and coated for 87% to 99% reflectivity at 1030nm. The path of the pump light is portrayed by the narrow dotted lines. The laser light is indicated by the double dotted lines. The pump mirrors are water cooled. The Yb:YAG assembly is water jet impingement cooled. The bottom surface of the Yb:YAG is HR coated so as to define one end of the laser resonator cavity. In the experiment, along with the usual power measurements, a thermal camera and Silicon CCD camera film the ramp up to full power. Fig.1(c) is a photograph of a mounted disk assembly, and Fig. 1(d) is a CAD drawing of the assemblies side view.

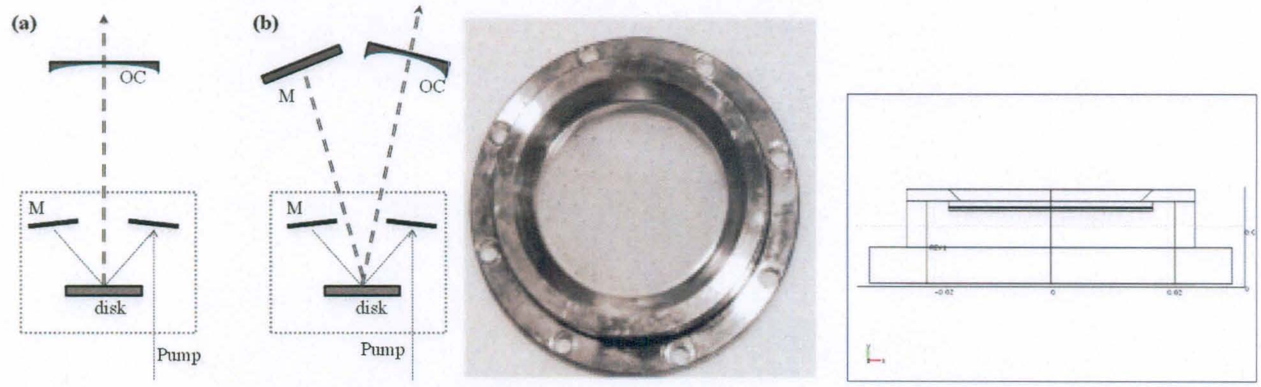

Figure 1. Experimental arrangement. (a) I-cavity. (b) V-cavity. (c) Photograph of a 35mm mounted disk assembly. (d) CAD drawing of thin disk assembly.

The 940 nm laser diode pumping system consists of six Jen-Optics 2.5 kW/25 bar-stack laser diodes with collimating spherical-cylindrical lenses, combined using a thick polarizing plate and homogenized in a 20 cm SupraSil rod providing 12.7 kW of maximum pump power. The output of the homogenizing rod was relay-imaged to produce a fourth order super-Gaussian pump profile. The pump beam is re-imaged eight times on the thin disk using a parabolic mirror insuring 90% absorption of the incident pump power during lasing. It was observed that the thin disk (TD) pump absorption saturates to 80% of the incident pump power in fluorescence (non-lasing) mode, with a blocked cavity mirror.

High Power Operation

To investigate the TD gain saturation, both I- and V-cavity configurations were examined. The typical power measurements are recorded. Output coupler mirrors ranging from 94% to 99% are utilized so as to obtain slope and threshold power. This Rigrod curve data for an 11 mm and 18 mm diameter pump spot sizes was collected and compared. The purpose is to evaluate the gain saturation characteristics of the two resonant cavities and to quantify the role (if any) of transverse amplified spontaneous emission in the capped thin disks. During operation, the laser diodes current was ramped up in roughly 10 sec and held at the operating pump level for 5 sec. Since the ramp time is shorter than the time constant of a large thermopile power meters (> 40 sec), a pickoff mirror and a large-area biased photodiode were used to measure the power. The photodiode was calibrated to a thermopile power meter at a cw output power of ~500W. During the ramping stage, the slope efficiency was monitored so that the pump diodes could be turned off in case of a sudden drop in the slope efficiency in order to prevent disk or optical coating damage. The thermal diffusivity of YAG (4.5 mm^2/s) yields a thermal diffusion time constant of ~ 0.35 sec in our 1.2 mm thick doped/undoped YAG composite structure. The actual time constant is much shorter considering that the heat generation occurs mostly in the 200 μm doped region. Therefore, the ramp and hold duration enabled equilibrium lasing and thermal conditions.

Figure 2 shows the output power and slope efficiency measured during the ramp as a function of pump power and intensity for both the V-fold cavity (4% output coupling) and the linear cavity (2% output coupling). The linear cavity achieved 6.5 kW output at ~ 60% slope efficiency, but the V-fold cavity achieved a maximum of 5.5 kW, before the control program shuts down the pump diodes due to a sudden drop in the slope efficiency at a pump intensity of 4.5 kW/cm2. This slope efficiency drop at a high pump intensity is a precursor to the cavity becoming unstable. This is chiefly due to the thermal expansion induced disk flexure. A simple cavity mode stability computation predicts a convex radius of curvature of -3 m. This curvature estimate amounts to > 20 waves sag across the disk. The real situation is more difficult to quantize. Thermal lensing measurement of a 980 nm probe beam bouncing off of the TD, see below, shows a complex wavefront. The linear cavity, on the other hand, was stable up to a stronger disk curvature of -1.5 m. This is due to the shorter linear cavity involving half the number of bounces off of the thin disk per round trip compared to the V-fold cavity. The ratio of the pump spot size to that of the fundamental cavity mode was ~ 10 at low pump power and approached ~ 5 before the V-fold cavity became unstable. This is due to the increase in the size of the lowest order fundamental cavity mode caused by the disk flexure.

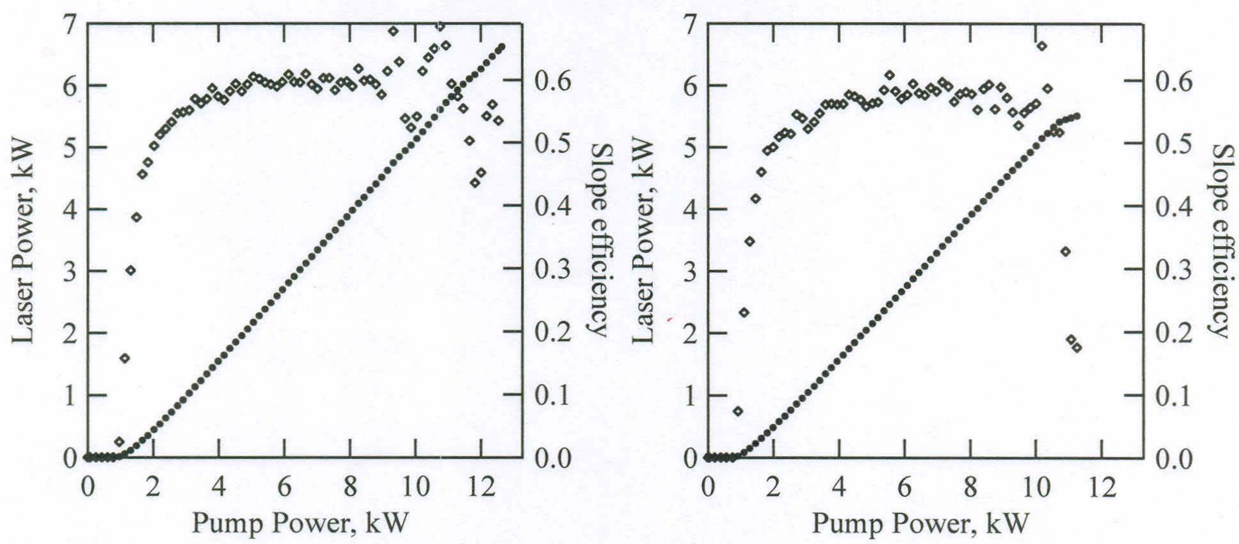

Figure 2. Laser power and efficiency (a) I-cavity. (b) V-cavity.

Thermal lensing

Thermal lensing of the lasing disk is measured by an expanded and collimated 980 nm fiber coupled semiconductor laser probe. The beam far-field profile was imaged on a camera 2.2 m away from the thin disk. Three thermal lensing contributions were identified; (1) thermal expansion induced negative lensing (disk acquiring a convex r.o.c.), (2) positive lensing due to the temperature profile towards the pump spot edge, and 3) a thermal imprint of the cooling nozzle. The far-field profile of the 7mm diameter probe beam reflecting off of the unpumped disk is shown in Fig. 3 (a) together with the outline of the 11 mm and 18 mm pump spots. Figure 3(a) is the baseline image. Figures 3 (b) and (c) show the probe near-field profile off of the pumped disk for the small and large pump spots of equal pump intensity, respectively. Thermal expansion induced negative lensing and the nozzle imprint is clearly demonstrated for the large pump spot in Fig 3 (c). The images are looking at the surface, see Fig. 1(c) for a visual reference. Positive lensing due to the pump-edge temperature profile is highlighted in the intense ring and smaller probe beam in Fig 3 (b). It is worth pointing out that thermal expansion induced disk flexure scales with the total pump power and not with pump intensity. That is why the V-fold cavity became unstable at a pump intensity of 4.5 kW/cm^2 for the 18 mm pump spot and why the cavity was still stable for pump intensities over 6 kW/cm^2 for the smaller

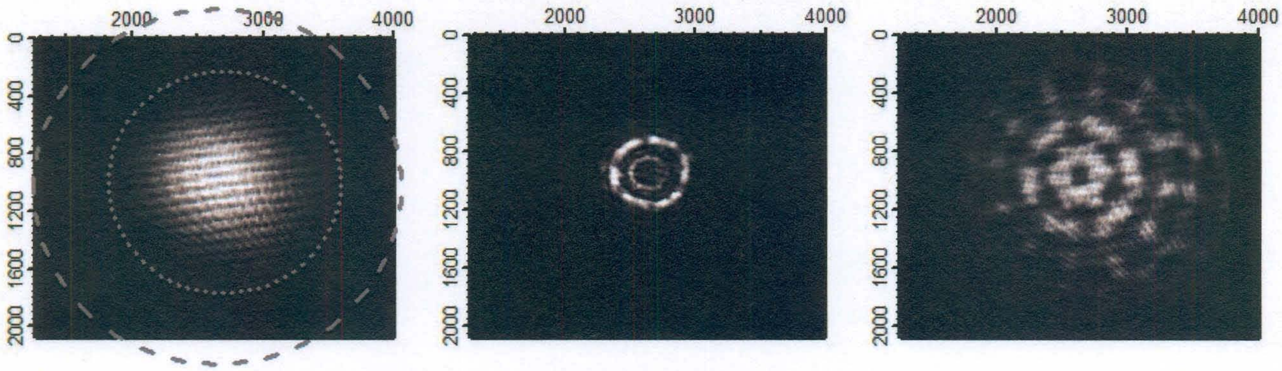

Figure 3. (a,left) Far-field profile of a 7mm diameter 980 nm probe beam reflecting off of the unpumped disk together with the outline of the 11 mm (dotted circle) and 18 mm (dashed circle) pump spots. (b, middle) and (c, right) show the probe profile off of the pumped disk for the small and large pump spots.

pump spot. A fluid flow/thermal conduction simulation (using cfDesign software) of our jet impingement cooling nozzle showed strong transverse variation of the water velocity and film coefficient. This translated to temperature variations of up to 40^o C for a heat load of 0.8 kW/cm^2 between points directly cooled and locations in between jets. The simulation points to complete washout of this transverse temperature variation, through radial heat conduction, in the interior of the undoped cap, in agreement with thermal camera images of the undoped cap (not shown). The pump induced nozzle thermal imprint is fully developed at a distance of ~ 30 cm away from the disk. This pattern complicated proper wavefront characterization.

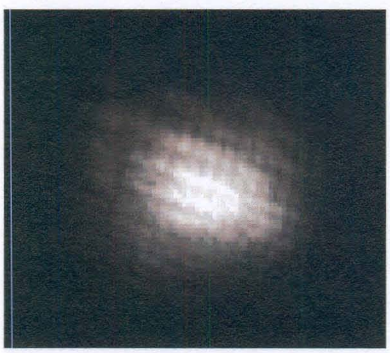

Figure 4. Probe beam from thin disk with SiC heat sink. No evidence of thermal lensing is seen.

It is possible that the preferential cooling of the disk, Figs. 3(b) and (c), may be alleviated by a redesign of the water cooling impingement mechanism. But initial attempts at a nozzle redesign did not alleviate the problem. Furthermore, the effect this will place on the heat removal capacity hasn't been examined. But the use of the intermediary heat sink

improves the outlook. Figure 4 shows the probe beam from a disk assembly that is mounted onto a SiC submount. Fig. 6 can be visually compared to Fig. 3(c). All evidence of the nozzle imprint is alleviated.

Cap temperature in lasing and ASE modes.

The temperature of the undoped cap, as measured by a thermal camera, was systematically higher in the lasing mode than during nonlasing/fluorescence mode (blocked cavity). The dependence of this excess heating on the output coupling percentage indicates the temperature increase is proportional to the intracavity intensity level. The rate of temperature increase with respect to the *absorbed* pump intensity is 23.8°C/(kW/cm^2) in fluorescence mode and 27.2°C/(kW/cm^2) in lasing mode for the linear cavity with 4% output coupling and reaches 35.1°C/(kW/cm^2) with 1% output coupling. The undoped cap in the V-fold has a slightly higher heating slope of 28.7°C/(kW/cm^2) and 38.1°C/(kW/cm^2) for 4% and 1% output coupling respectively. These estimates take into account the pump absorption saturation (reduced absorption) in the fluorescence mode. Assuming a temperature gradient in the doped region and a constant temperature throughout the undoped cap, the fluorescence mode temperature increase implies that 12% of the absorbed power is dissipated as heat which is close to the 11% quantum defect. With power extraction in the lasing mode, we expect a lower temperature, since more of the deposited energy leaves the TD in the laser output beam. The undoped cap temperature reached 185°C for the maximum output power of 6.5 kW. This excess heating at the AR coating, imposed a lower (upper) limit on the pump spot size (pump and extracted power intensity) and therefore necessitated the use of a larger pump size to fundamental cavity mode size ratio.

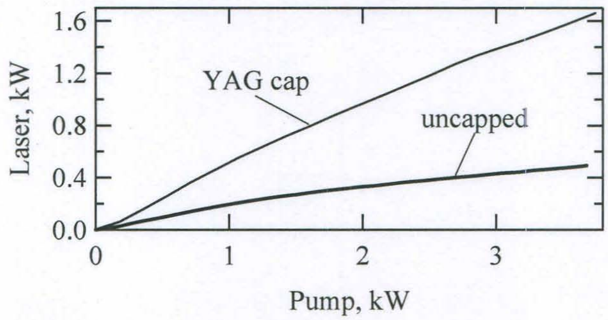

Figure 5. Laser power curves for YAG/Yb:YAG and uncapped Yb:YAG samples.

Performance between YAG capped and un-capped Yb:YAG material.

With the availability of heat sinks to provide structure, Yb:YAG lasing can be examined with and without the undoped YAG caps. In this case, the result is striking. For the tests presented here, the particular material used in both cases is similar but unfortunately not of high quality. Although disks were mounted upon diamond heat sinks, the vendor inadvertently used a thermally insulative epoxy for attachment. Still, the fact that the two samples are identical allows a direct comparison to be made. The disk diameter is 35mm with a clear aperture of 25mm. Figure 5 shows the laser power versus pump for the two cases. The capped disk develops a slope efficiency of 40% but this is substantially greater than the uncapped sample, which only exhibits 20%. Furthermore, the latter's slope efficiency turns sub-linear at higher powers.

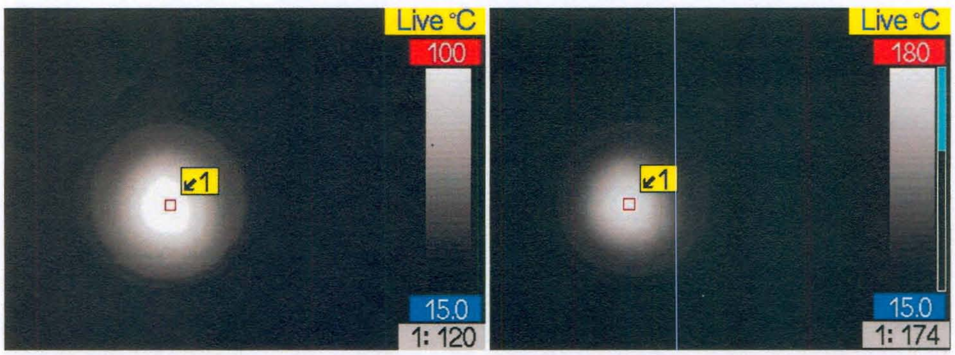

Figure 6. Surface temperatures at 3.7kW. Left: YAG / Yb:YAG. Right: uncapped Yb:YAG.

In Figure 6, thermal images are shown of both disks. The central 18mm of each disk is pumped with 3.7kW power. Figure 6(a, left) is the YAG capped sample. It reaches a maximum temperature of 120 C. Figure 6 (b,right), the uncapped sample, excessively heats to a much higher temperature at 174 C. Although there may be differences in the number of material defects, the primary difference is the ASE amplification and re-absorption within the disk.

3. NUMERICAL MODELING

Concurrent with the experimental inquiry, analytical and numerical techniques are employed. For the numerical approach, COMSOL Multiphysics is used. COMSOL is commercial software that applies numerical techniques based on the finite element method for the spatial discretization. The disk geometry along with the appropriate material constants are programmed. Cooling is assumed to be constant across the bottom surface of the disk. This is unlike the real situation where cooling is via spray jets. But it is sufficient to compute the overall disk deformation and surface temperatures. The model does include thin layers such as the epoxy layer that is necessary to attach SiC and Diamond to the HR coatings on the Yb:YAG.

The high power laser described above, without heat sink component and described in Fig. 2, ultimately succumbed to cavity instability. Using absorbed pump powers based on the maximum observed laser power, 890W, along with estimated thermal transfer coefficients, $5x10^4$ W/m^{2}K, the deformation and surface temperatures are computed. Figure 7 shows the surface temperature and deformation of the disk across its diameter. The disk's expansion is checked by the cooler stiff CuW cap that forces the warpage. The deformation shows several waves of sag at the edges. A complete computation of the wave front would have to include contributions to the refractive index from the temperature variation across the disk.

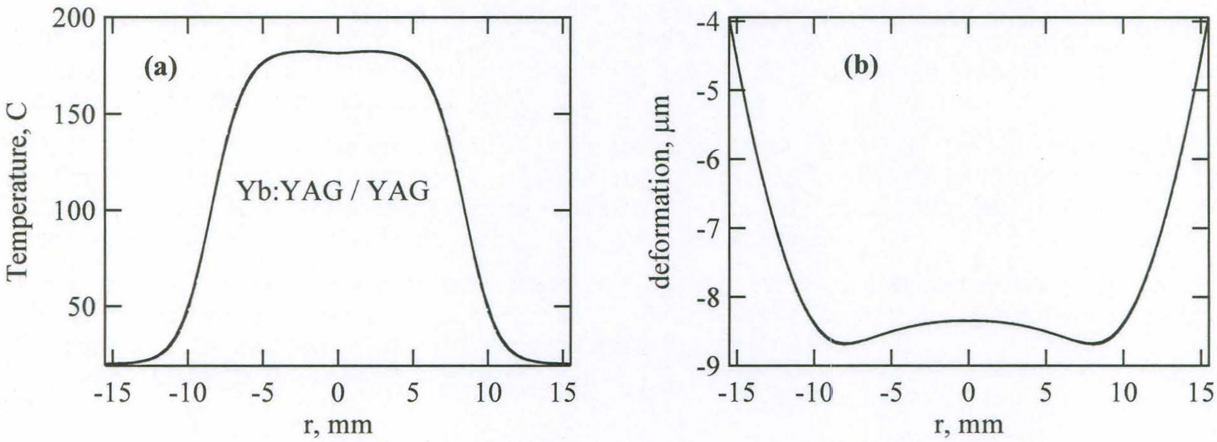

Figure 7. (b) YAG-Yb:YAG Disk deformation across the diameter of the disk under a severe heat load.

The surface temperature of the disk assembly is computed for various cases. Figure 8 shows the heating for the case of the capped YAG-Yb:YAG and the uncapped Yb:YAG sample, see the experimental data portrated in Figs. 5 and 6. COMSOL by itself is unable to theorize the heating due to ASE. Our model accounts for ASE heating increasing the heat load until the model agrees with experiment. This increase is a 1.75 factor for the capped disk and a 2.75 factor for the uncapped disk. As seen experimentally, the laser slope efficiency suffers since thermally energized electrons incresingly populate the lower lasing level.

Finally Fig. 9 plots the surface temperature of the disk assembly under a 500W heat load, when incorporating a heat sink. The case of SiC and diamond is shown. Diamond possess a thermal conductivity nearly 5 times greater than that of SiC. However, in revenge, the thermal expansion coefficient of SiC is much closer to that of Yb:YAG than that of diamond, which will be of significance if extreme thermal cycling is expected.

The idealized model scenario only exists when the material, optical coatings, and attachment techniques are perfected. These are engineering challenges that can be overcome. The more fundamental problem to attack lies with the inevitable ASE production in the Yb:YAG. This is difficult to theoretically predict.

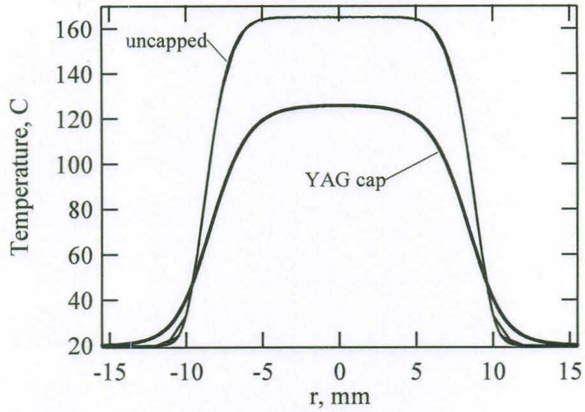

Figure 8. surface temperature across disk for capped and un-capped samples.

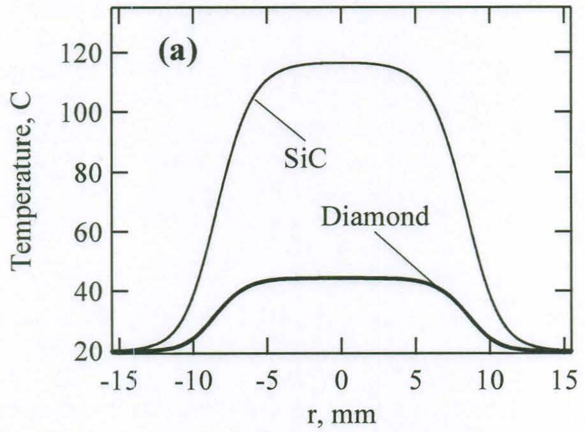

Figure 9. Modeled surface temperature in the radial direction for SiC and Diamond heat sinks.

4. SUMMARY

The long term objective of Air Force Research Laboratory thin disk work is towards high beam quality. Correspondingly this research, initially directed at generating high power lasers, turned towards thermal management problems. Mitigating these issues leads to minimization of disk deformation, improvement in overall efficiency, and increases in the total laser power. A further necessary step in this direction pertains to understanding all aspects of thin disk lasers. physics-based research is being conducted regarding small signal gain, amplified spontaneous emission, and thermal issues. Mechanical engineering problems focus on improvements in associated materials.

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